Sensitivity of microwave and FIR spectra to variation of fundamental constants

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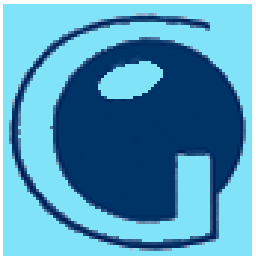

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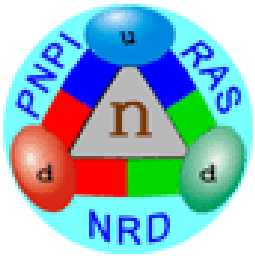

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Fundamental constants in atomic physics

There are three fundamental constants, which influence atomic and molecular spectra:

- Fine structure constant $\alpha = e^2/(\hbar c)$;
- Electron to proton mass ratio $\beta = m_e/m_p$;
- Nuclear gyromagnetic ratio g_n.

When we are studying variation of fundamental constants, we are looking for lines with high sensitivity to the variation of fundamental constants. The dimensionless sensitivity coefficients are defined as:

$$\frac{\delta\omega}{\omega} = K_\alpha \frac{\delta\alpha}{\alpha} + K_\beta \frac{\delta\beta}{\beta} + K_g \frac{\delta g_n}{g_n}.$$

In astrophysics such frequency shifts lead to the difference between the apparent and actual redshifts z' and z:

$$\frac{\delta\omega}{\omega} = -\frac{z' - z}{1 + z'}$$

When we observe two lines with different sensitivities, their apparent redshifts will differ if fundamental constants has changed during the time passed:

$$\frac{\delta z'}{1 + z'} = -\Delta K_\alpha \frac{\delta\alpha}{\alpha} - \Delta K_\beta \frac{\delta\beta}{\beta} - \Delta K_g \frac{\delta g_n}{g_n}.$$

Sensitivity coefficients for different wavebands

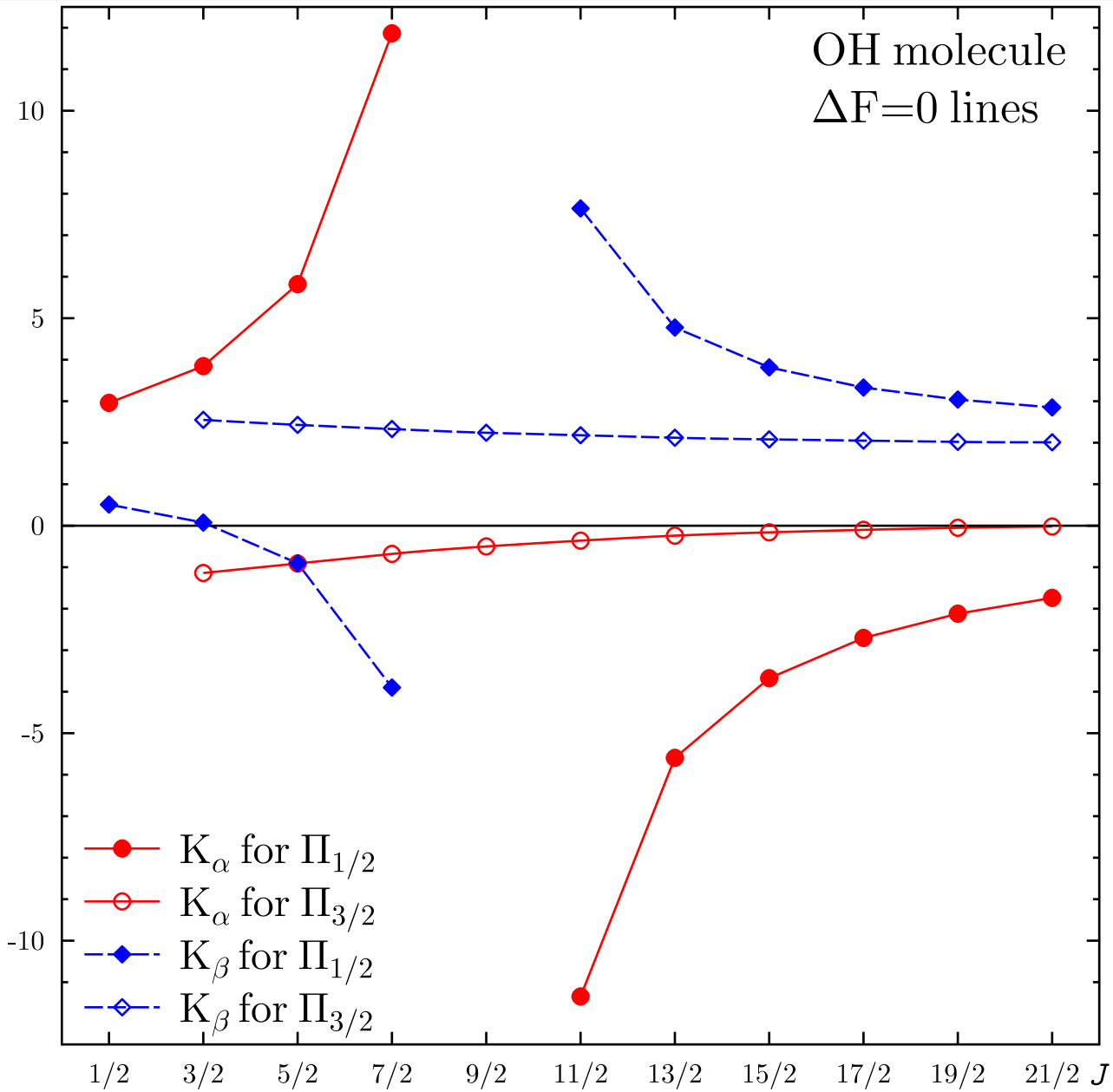
Transition	K_α	K_β	K_g
Optical and UV bands			
typical E1-transition in atoms	$10^{-2} - 10^{-1}$	10^{-3}	10^{-7}
electronic transitions in molecules	10^{-2}	10^{-2}	10^{-7}
Microwave and FIR bands			
fine-structure M1-transitions	2	0.0	0.0
vibrational transitions	0.0	0.5	0.0
rotational transitions	0.0	1.0	0.0
21-cm hyperfine transition in hydrogen	2.0	1.0	1.0
18-cm Λ-doublet line in OH	-1.14	2.55	0.0
1.25-cm inversion line in NH_3	0.0	4.5	0.0

Spin decoupling in Λ-doublet transitions

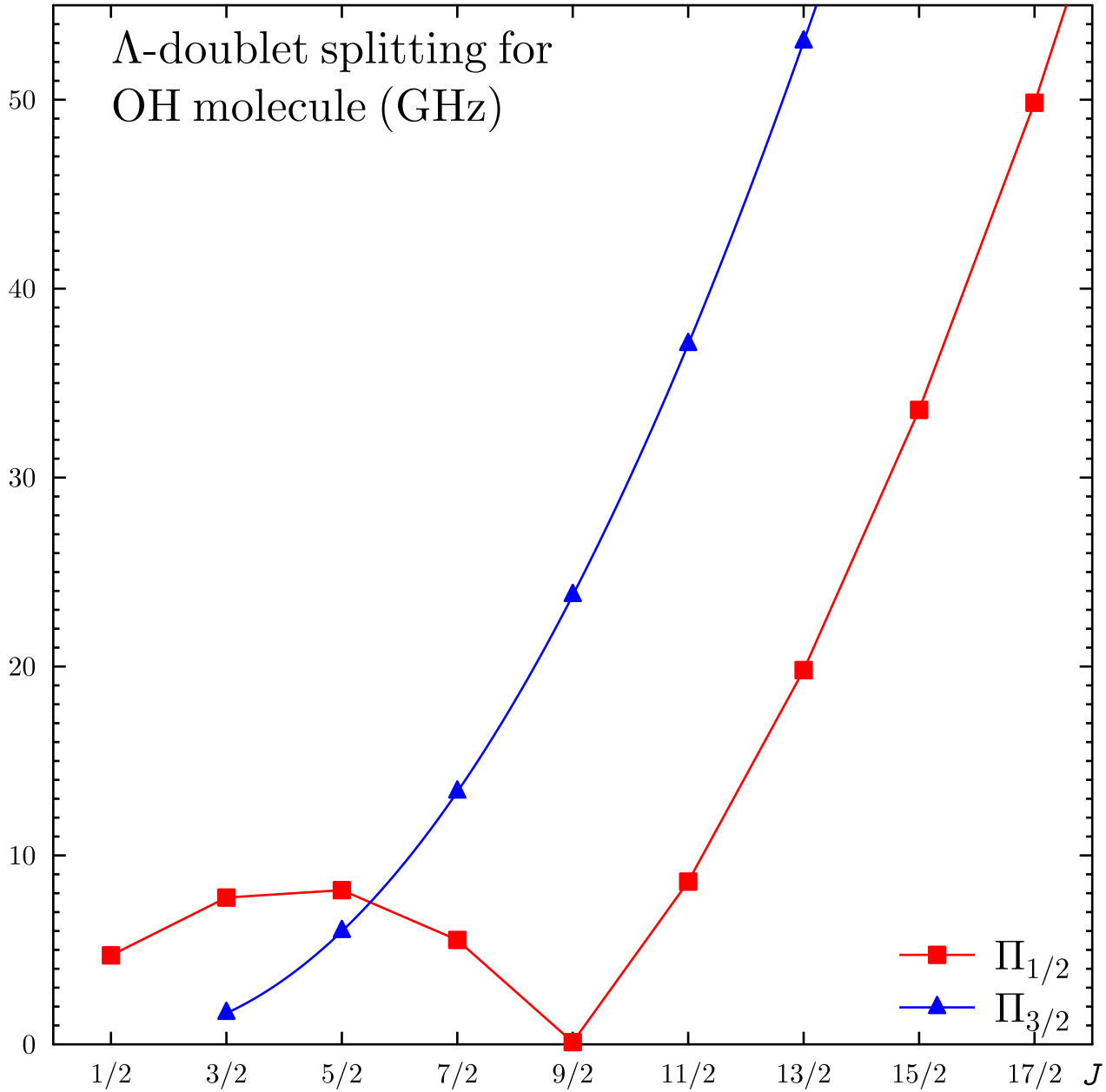
In OH and CH molecules electron spin $\boldsymbol{S}$ is weakly coupled to molecular axis. As rotational quantum number J grows, spin $\boldsymbol{S}$ decouples from the axis. This causes transition from Ω-doubling regime for small J values to Λ-doubling regime for higher rotational states.

For the higher electronic state ($\Pi_{1/2}$ for OH and $\Pi_{3/2}$ for CH) decoupling leads to level crossing and to enhancement of sensitivity coefficients K_α and K_β. Transition frequencies and sensitivity coefficients for lower electronic state have smooth dependence on quantum number J.

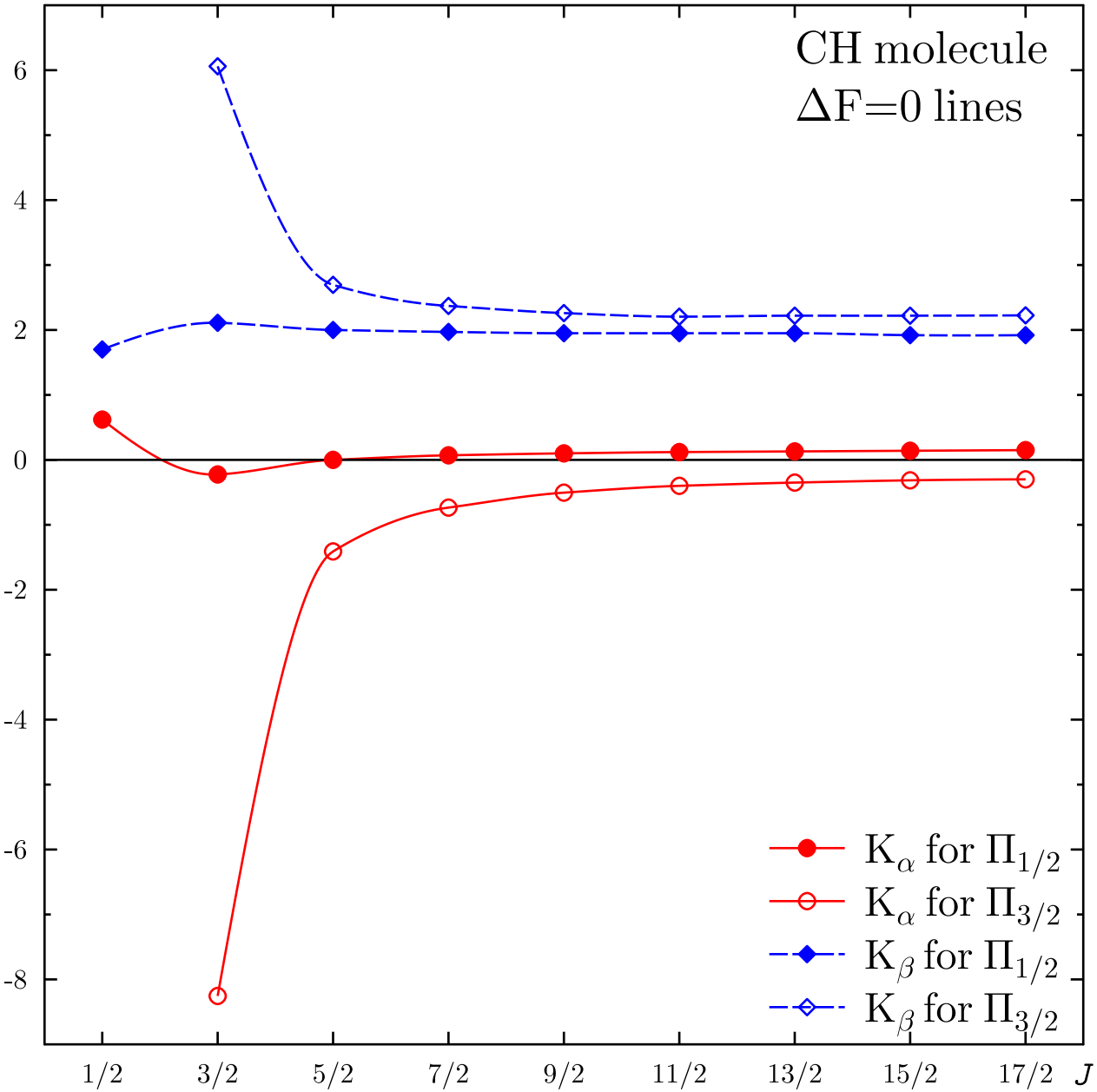
Sensitivities of Λ-doublet transitions in OH



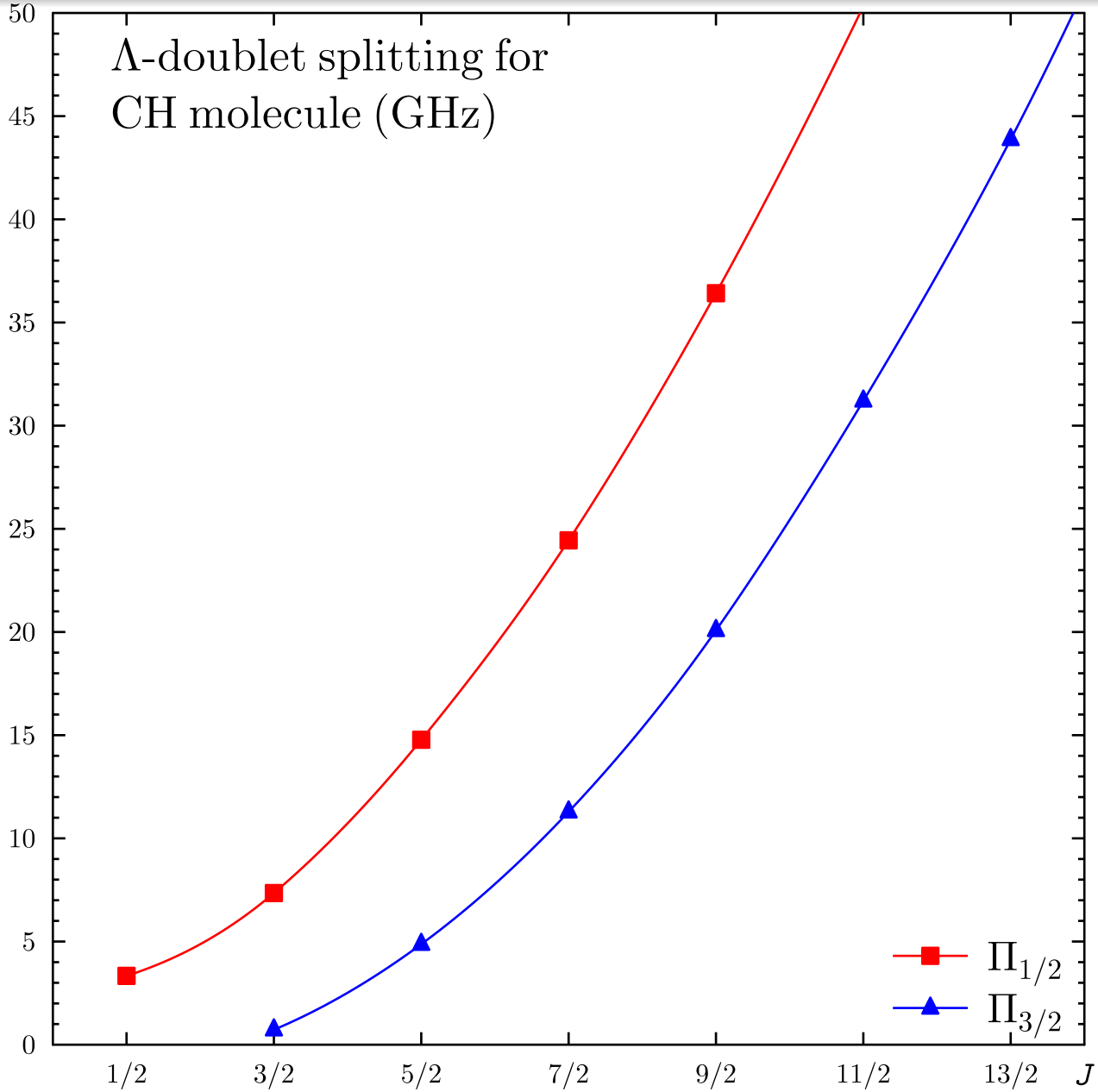
Frequencies of Λ-doublet transitions in OH



Sensitivities of Λ-doublet transitions in CH



Frequencies of Λ-doublet transitions in CH

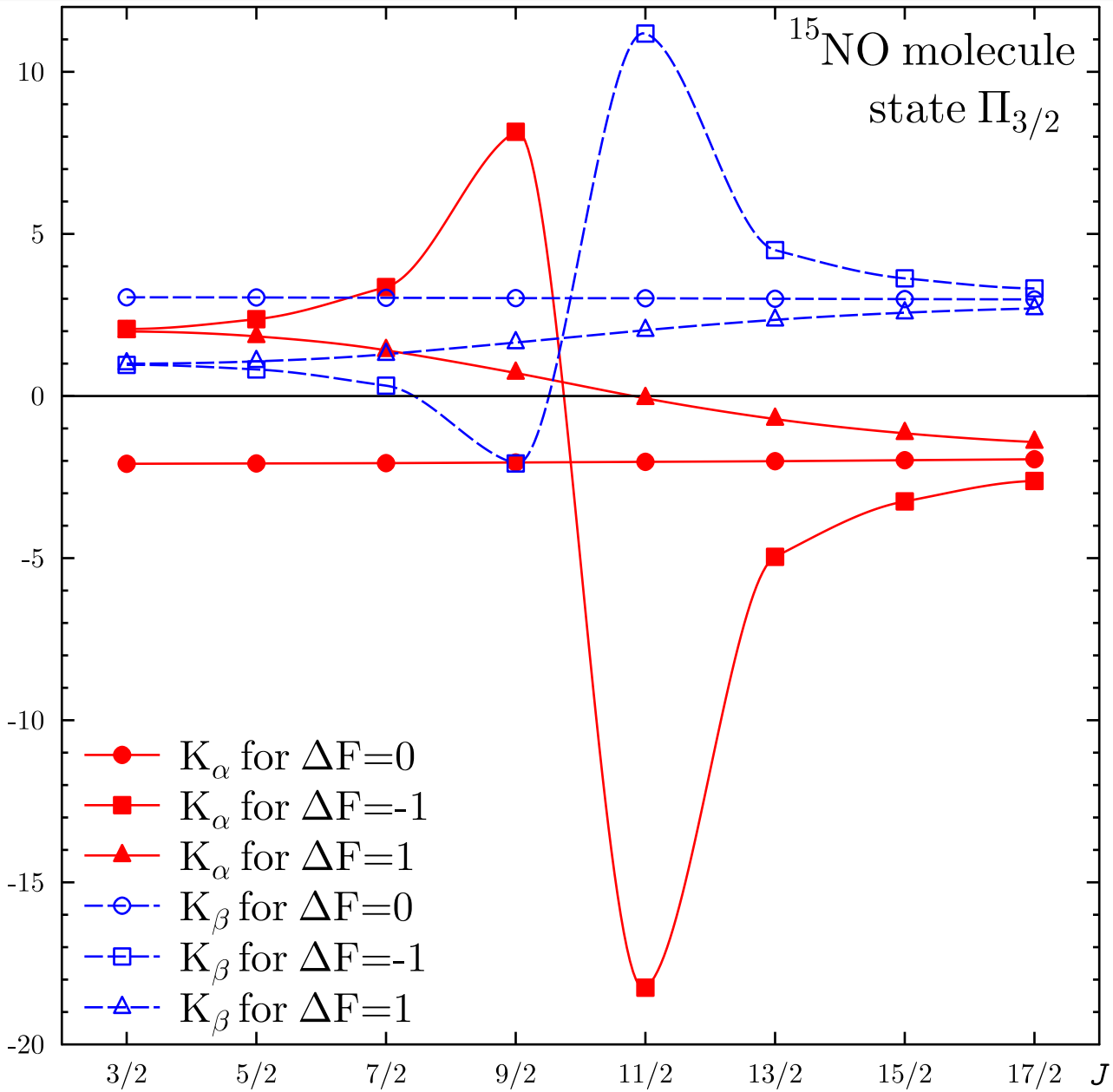


Hyperfine anomaly in Λ-doublet transitions

For $\Pi_{3/2}$ states of molecules ^{14}NO, ^{15}NO, and ^{7}LiO the hyperfine structure is comparable to Λ-doubling. For some values of J the hyperfine energy can almost cancel Λ-doubling leading to anomalously small transition frequencies. This causes enhancement of the sensitivity to all three fundamental constants.

^{15}NO has simplest hyperfine structure where each Λ-doublet has four components: two with $\Delta F = 0$ and two with $\Delta F = \pm 1$. Both $\Delta F = 0$ transitions have very close frequencies and sensitivity coefficients.

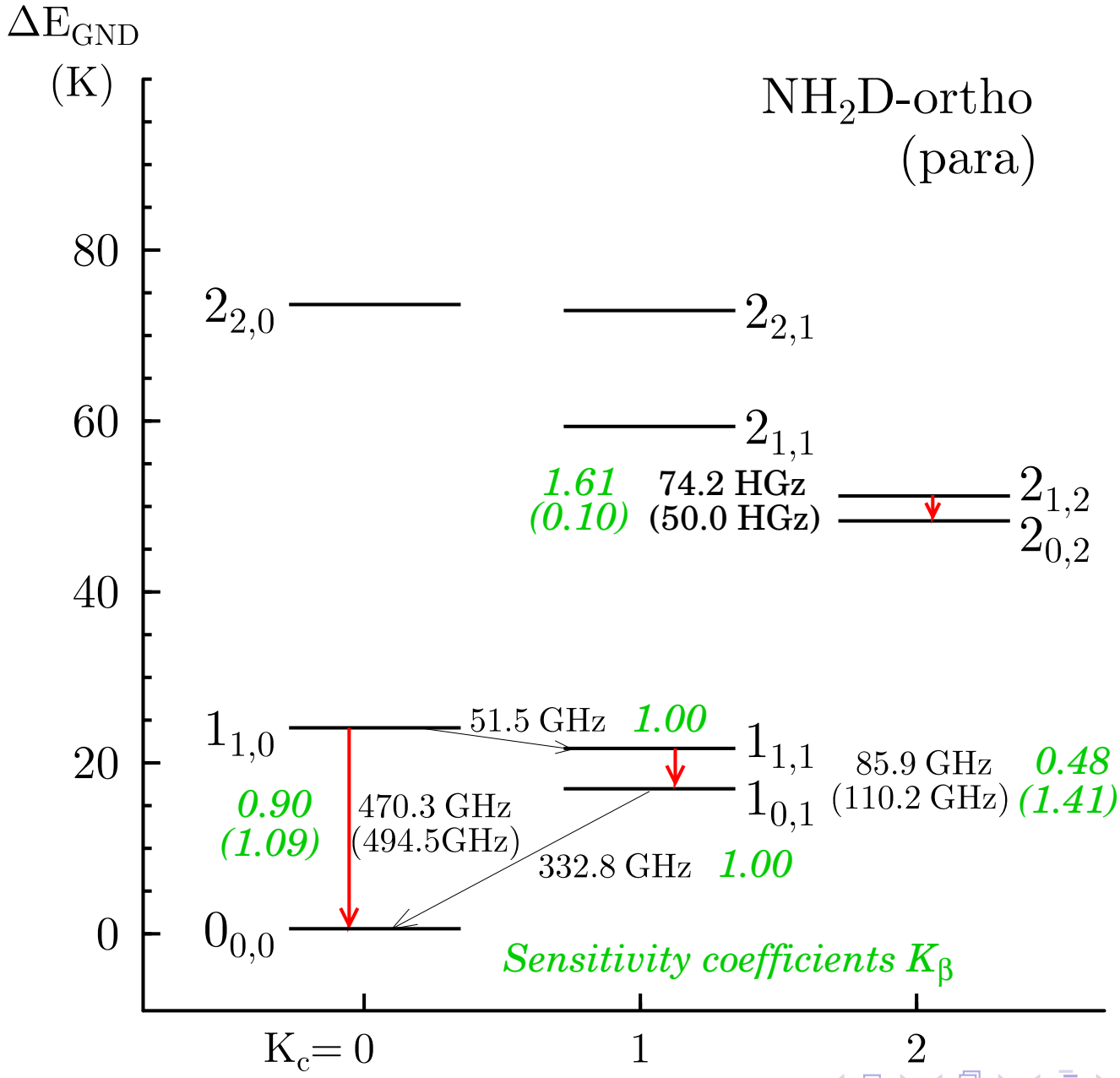
Λ-doublet transitions in ^{15}NO (hyperfine anomaly)



Rotation-inversion spectrum in deuterated ammonia

Inversion transitions in NH_3 and ND_3 are highly sensitive to β-variation, $K_\beta \approx 5$, while rotational transitions have normal sensitivity, $K_\beta = 1$. Inversion transitions in partly deuterated ammonia NH_2D and ND_2H are mixed with rotational transitions. This leads to strong dependence of sensitivity coefficients on rotational quantum numbers and to difference between *ortho* and *para* species.

Rotation-inversion spectrum of $^{14}NH_2D$



Conclusions

- FIR and microwave transitions are typically 100 times more sensitive to α and β variation than optical transitions. This leads to significant suppression of systematic effects caused by Doppler noise.
- Sensitivity of Λ-doublet transitions in diatomics and inversion-rotation transitions in deuterated ammonia strongly depends on quantum numbers. This opens possibility to use different transitions of the same species for studies of the variation of fundamental constants. Therefore Doppler noise can be additionally suppressed.
- In microwave spectra there is no systematics caused by isotope shifts as the spectra from different isotopes are well resolved.

Collaborators

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- Alexander Lapinov
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